Available online at www.sciencedirect.com

ScienceDirect

Procedia Technology 25 (2016) 1320 – 1334

Procedia Technology

Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science and Technology (RAEREST 2016)

Dynamic Simulation and Validation of a Vent and Safety Valve for Cryogenic Flight Tanks

A. Manimaran[a], Somashekhar S. Hiremath[b], Panuganti Shekhar K[a,b] *

[a]*Liquid Propulsion Systems Centre, Valiamala, Trivandrum-695547, India*
[b]*IIT Madras, Adyar, Chennai-600036*

Abstract

High Thrust Cryogenic Rocket Stages entail the use of a Vent and Relief Valve which can cater to a higher discharge rate. The Vent function is called for during ground servicing operations like tank chilling and pressurant replenishment and during flight to take care of the decrease in ambient pressure and boil-off losses. The Relief function acts as a redundant feature to protect the tanks from catastrophic failure due to structural damage caused by over-pressurization. Nevertheless, this valve needs to be characterized for both these functions during ground tests. This paper describes the modelling of and experimentation on an Inverted Type Pilot Operated Vent and Safety Valve. A mathematical model for simulating the dynamic behavior of this tank-mounted valve is developed. For this, a set of non-linear, first order, coupled ordinary differential equations, based on laws of conservation of mass and energy, are derived using fixed control volume approach. The numerical solution of these equations is obtained using fourth order Runge-Kutta method. The pressure, temperature, flow rate, seat stress and lift thus obtained are plotted to find the characteristic parameters such as cracking pressure, full flow pressure, reseal pressure, opening and closing response, tank pressure decay rate and full flow rate. The valve performance is studied for the effect of main valve outlet orifice and the pilot valve outlet orifice using these simulations. These results are validated by comparing it to the test results.

Peer-review under responsibility of the organizing committee of RAEREST 2016

Keywords: Cryogenic; Inverted Type Pilot Operated Vent and Safety Valve; dynamic simulation; non-linear; mathematical modelling; validated

* Corresponding author. Tel.: +91-471-256-7090; fax: +91-471-256-7984.
E-mail address: a_manimaran@lpsc.gov.in

Peer-review under responsibility of the organizing committee of RAEREST 2016
doi:10.1016/j.protcy.2016.08.232

Nomenclature

A	cross sectional area of control volume [m2]
A_{b1}	main valve bellow effective area [m2]
A_{b2}	pilot valve bellow effective area [m2]
A_{in}	area of inlet port of control volume [m2]
A_{st}	area of pilot valve stem [m2]
A_{s1}	main valve seat area [m2]
A_{s2}	pilot valve seat area [m2]
B_1	main valve bellow stiffness [N/m]
B_2	pilot valve bellow stiffness [N/m]
C_d	co-efficient of discharge
C_p	specific heat at constant pressure [J/kgK]
C_v	specific heat at constant volume [J/kgK]
d_1	main valve inlet port size [m]
d_2	communication orifice size [m]
d_3	main valve outlet orifice size [m]
d_4	pilot valve inlet port size [m]
d_5	pilot valve outlet orifice size [m]
d_{s1}	main valve seat diameter[m]
d_{s2}	pilot valve seat diameter[m]
FB_1	main valve bellow initial load [N]
FB_2	pilot valve bellow initial load [N]
FS_1	main valve spring initial load [N]
FS_2	pilot valve spring initial load [N]
K_1	main valve spring stiffness [N/m]
K_2	pilot valve spring stiffness [N/m]
M_1	mass of main poppet[kg]
M_2	mass of pilot poppet [kg]
$\dot{m}_c$	mass flow rate into the tank[kg/s]
$\dot{m}_{ij}$	mass flow rate from chamber i to j [kg/s]
P_i	pressure in chamber i [bar]
R	ideal gas constant [J/kgK]
T_c	temperature of fluid flowing into the tank [K]
T_i	temperature in chamber i [K]
t	time [s]
V_i	volume of chamber i [m3]
x	displacement of moving element [m]
x_1	lift of main poppet [m]
x_2	lift of pilot poppet [m]
$\dot{x}$	velocity of moving element [m/s]
$\dot{x}_1$	velocity of main valve poppet [m/s]
$\dot{x}_2$	velocity of pilot valve poppet [m/s]
$\ddot{x}_1$	acceleration of main valve poppet [m/s2]
$\ddot{x}_2$	accelerationof pilot valve poppet [m/s2]
γ	ratio of specific heats
1	tank
2	main valve chamber
3	main valve outlet chamber
4	main bellow chamber
5	pilot valve chamber

6	pilot valve outlet chamber
7	ambient

1. Introduction

A Cryogenic Liquid Propulsion Stage of any launch vehicle commonly uses liquid hydrogen and liquid oxygen as propellants. Liquid hydrogen is stored at a temperature of 20K and liquid oxygen is stored at 90K with pre-pressurization. During pre-filling ground servicing operations of the stage like tank chilling, these cryogenic propellants are supplied at a specified flow rate into the tank. The tank, being at a temperature much higher than the propellant temperature, vaporizes the propellants which causes an increase in the tank pressure. Any extra pressure above the maximum operating pressure of the tank has to be discharged into the ambient to protect the tank from structural damage. Another ground servicing operation which can cause an accidental pressure rise is the pressurant replenishment operation. After lift-off, as the vehicle gains altitude, the ambient pressure decreases. This causes an increase in the pressure differential across the tank which again has to be discharged to the atmosphere. Any heat transfer between the tank and the surroundings results in propellant boil-off. These reasons call for a relief valve, working at cryogenic temperatures, capable of opening at a set pressure and discharging the excessive volume of gas to the surrounding to bring back the pressure within allowable limits. The relief valve also prevents a catastrophic failure in case of pressure rise due to stage pressurization system failure.

Sometimes the relief valve may also have an added function of venting, in which the pressurant is intentionally vented by opening the relief valve using a pneumatic command. This valve is then called as a vent and relief valve [4]. A relief valve is called a safety valve when the valving element goes to its full open position [4] (also called pop opening) as soon as the pressure rises slightly above the set pressure. Relief valves are of two types; direct acting and inverted. In direct acting relief valve, the load on the seating element goes on decreasing as the working pressure approaches the cracking pressure. Hence it is prone to leakage at pressures near the set pressure of the valve. This phenomenon is known as dribbling [4] and causes unnecessary loss of pressurant. This is avoided by using an inverted relief valve where the seat load goes on increasing with pressure, reducing dribble.

Normally, the flow rate to be handled by cryogenic relief valves is high. A relief valve which meets such a high flow rate must have a higher seat diameter. This in turn calls for a larger and heavier spring [4] for a given set pressure which increases the inert mass and envelope of the valve. In order to overcome this, a pilot valve is used which actuates the main valve. The pilot valve is a direct acting type valve with a small seat diameter.

The design and analysis of this pilot operated inverted construction is complicated and is done using characteristic steady state equations. The operating characteristics of valve such as full flow pressure, reseal pressure, opening and closing response and time-varying parameters like flow rate, pressure and temperature in the tank and valve, lift of valving element cannot be estimated using these equations. These parameters are very important in the design of cryogenic stage systems as they are necessary for the estimation of pressurant losses, the amount of pressurant required, working to relief pressure range and tank structural safety margin. The flow rate through the valve at full open condition determines the adequacy of the relief valve in a given system. The flow rate and opening of the relief valve are controlled by the back pressure generated. The static equations are not capable of predicting this parameter. In order to characterize the valve with respect to these parameters, a dynamic model needs to be developed.

Literature survey suggests that a dynamic model for a pneumatic pilot operated inverted safety valve does not exist. Dasgupta and Karmakar (2002) [2] generated a dynamic model of a hydraulic pilot operated relief valve with constant input pressure using bond graph simulation technique. The simulation using the same technique used in this paper was carried out by Nabi et.al. (2000) [1] for a dome loaded pressure regulator. In this paper, a dynamic model of a vent and safety valve mounted on a tank is generated using basic equations of conservation of mass and energy. The first section of the paper explains the construction and working of the valve. The valve is then modeled by converting each chamber into a control volume with inlet and outlet orifices. Conservation of mass and energy equations are applied to each of these volumes to derive the differential equations governing the pressure and temperature at each volume. The solution of the differential equations is obtained using fourth order Runge-Kutta method [5]. The motion of dynamic elements is modeled using Newton's second law which is further integrated to find velocity and displacement of the moving parts. The valve is further studied for the effect of different elements on its performance.

2. Construction and Working

The Vent and Safety valve described here is designed for a pneumatic medium and is capable of working at cryogenic temperatures. The simplified construction of the valve is shown in fig.1. It consists of a main valve and a pilot valve mounted on the main valve body. The main valve is of inverted type. The main valve poppet sub-assembly contains a soft seat which seals against the main valve body. A helical compression spring provides the necessary seat load. A metallic bellow is welded to the poppet on one side and the other side is joined to the main valve body. An orifice called the communication orifice drilled in the main valve body allows the inlet pressure to be communicated to the bellow internal chamber. With an increase in the inlet pressure, the force due to the pressure acting on the effective area of the bellow increases which increases the seat load. This allows the use of a low stiffness light spring to achieve good leak tightness. The bellow chamber is connected to the pilot valve chamber through an orifice of size higher than the communication orifice. An outlet volume is provided at the downstream of the main valve poppet to generate back pressure which aids opening of the main valve. It also houses the outlet orifice. The pilot valve chamber is sealed from the ambient using a pilot poppet sub-assembly. The pilot valve also contains a small outlet volume having an orifice. The inlet pressure is communicated to the pilot valve sensing bellow external as shown in the figure 1. The pilot valve is a direct operated relief valve where the force on the sensing bellow due to the inlet pressure lifts the poppet against the spring load. A loading element is tightened or loosened to adjust the set pressure of the valve. A mechanical stopper limits the stroke of both the valves. The main valve poppet is connected to the command piston using a connecting rod. In vent mode, a pneumatic command supplied under the piston acts against the command spring and lifts the main valve poppet. Specialized seals capable of working at cryogenic temperature and compatible with the propellants are used to prevent external leakage.

This valve is mounted on a propellant tank using an inlet flange. The tank pressure is communicated to the main valve chamber, bellow chamber, pilot valve chamber and the sensing bellow through different orifices in the valve. With increase in inlet pressure from the working pressure to the cracking pressure, the pressure and hence the force on the main poppet increases whereas that on the pilot poppet decreases. The leak tightness achieved in the main valve is the prime advantage of an inverted type. As soon as the inlet pressure rises to the set pressure of the pilot valve, the opposing forces on the pilot poppet cancel out and the poppet starts lifting proportionally with any further inlet pressure rise. The opening of the pilot poppet causes the bellow internal pressure to decay since the size of the communication orifice (inflow) is lower than the pilot valve inlet orifice (outflow). This results in a pressure differential across the main bellow with higher pressure at the external and lower in the internal. This resultant opening force is opposed only by the spring force which is very small compared to the pressure-differential force. This causes the main poppet to open suddenly or pop to its full open position. The gas is discharged from the main valve chamber to the ambient through the outlet chamber. The pressure drops across the main poppet as flow is established and a back pressure is generated in the outlet chamber. The back pressure further acts on the main poppet and keeps it open. The flow and the back pressure are determined by the size of the outlet orifice. This flow reduces the pressure inside the tank and as pressure drops below the full open pressure of the pilot valve, the pilot poppet starts closing. At a particular pressure called the reseal pressure, the pilot poppet closes and becomes leak tight. This increases the pressure inside the bellow chamber and after attaining a particular pressure, the main valve poppet closes ceasing the main valve flow. The closing of both poppets is influenced by the back pressure. The opening response and the closing response of the valve are highly dependent on the size of the communication orifice and the pilot valve outlet orifice. The closing response is also affected by the size of the main valve outlet orifice.

3. Assumptions

The analysis is carried out assuming that the valve is mounted on a tank. In order to simplify the model, following assumptions are made:

- The force on each element of the valve is calculated assuming uniform pressure distribution over the entire area considered.
- The frictional force on the moving elements is neglected.
- The expansion and compression processes inside the valve and tank are assumed to be isentropic. This is valid since the processes occur much faster (due to high flow rate) than the heat transfer.[1]
- The flow forces acting on the valve elements are neglected since they are small compared to the pressure forces.
- The forcing function for the pressure rise inside the tank is an inflow of a given amount of gas at particular temperature.
- The heat transfer between gas and valve body and between the valve body and surroundings is neglected.
- A control volume approach has been applied to model the valve. Hence the pressure in a given volume is assumed to be uniform and a sharp pressure drop is assumed to take place across an orifice.
- All springs are assumed to be linear.[2]
- The analysis is carried out for an ideal gas since the operating pressures are moderate.
- The specific heats of the working medium are assumed to be constant.
- The co-efficient of discharge for different orifices is assumed to be constant and is 0.8.

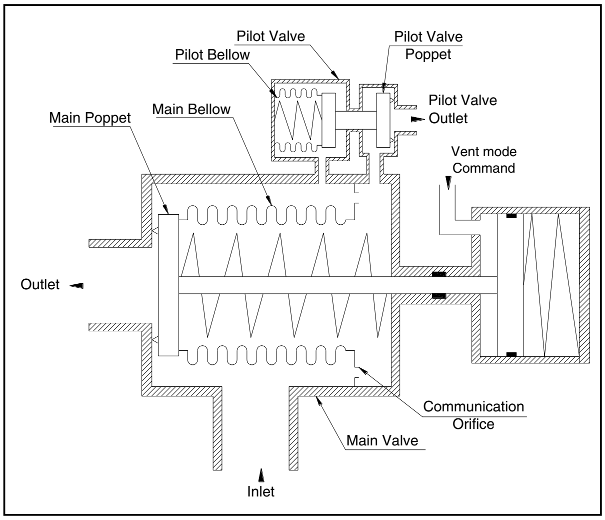


Fig. 1. Vent and Safety Valve

4. Governing Equations

The governing equations are derived by applying the laws of conservation of mass and energy to a fixed control volume. The control volume and the properties of fluid entering and leaving it are shown in fig.2.

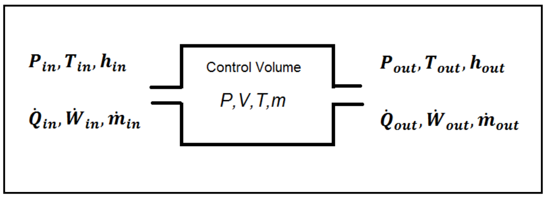


Fig. 2. Control volume approach

The law of conservation of mass [3] for the control volume can be written as

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \tag{1}$$

The law of conservation of energy [3] applied to the control volume gives

$$\frac{dE}{dt} = \dot{E}_{in} - \dot{E}_{out} \tag{2}$$

The rate of energy [3] entering into the system is

$$\dot{E}_{in} = \dot{Q}_{in} + \dot{m}_{in}h_{in} + \dot{W}_{in} \tag{3}$$

Since no heat is supplied and no work is done on the control volume, $\dot{Q}_{in} = 0, \dot{W}_{in} = 0$ and $\dot{E}_{in} = \dot{m}_{in}h_{in}$. For an ideal gas with constant specific heat, the rate of energy transfer into the system $\dot{E}_{in} = \dot{m}_{in}C_p(T_{in} - T_{ref})$. For a control volume whose volume does not change with time and which does not transfer any heat, the rate of energy transfer out of the system is given by $\dot{E}_{out} = \dot{m}_{out}C_p(T_{out} - T_{ref})$.

The rate of change of energy of the control volume is

$$\frac{dE}{dt} = \frac{dU}{dt} \tag{4}$$

$$U = mC_v(T - T_{ref})$$

where T_{ref} is the reference temperature.

The equation of state for an ideal gas is given by

$$PV = mRT \tag{5}$$

Taking log and differentiating w.r.t time at constant volume gives

$$\frac{1}{P}\frac{dP}{dt} = \frac{1}{m}\frac{dm}{dt} + \frac{1}{T}\frac{dT}{dt} \tag{6}$$

Using equations (1), (2), (3),(4) and (6),the rate of change of pressure w.r.t time in a control volume with constant volume is given by[1]

$$\frac{dP}{dt} = \frac{\gamma R}{V}(\dot{m}_{in}T_{in} - \dot{m}_{out}T_{out}) \tag{7}$$

and the rate of change of temperature w.r.t. time is[1]

$$\frac{dT}{dt} = \frac{RT^2}{VP}\left(\left(\gamma\frac{T_{in}}{T} - 1\right)\dot{m}_{in} - (\gamma - 1)\dot{m}_{out}\right) \tag{8}$$

When work is done by the system i.e. the volume of control volume increases w.r.t. time, some energy flows out of the control volume as work hence

$$\dot{W}_{out} = P\frac{dV}{dt} \tag{9}$$

For time varying volume Equation (6) becomes

$$\frac{1}{P}\frac{dP}{dt} + \frac{1}{V}\frac{dV}{dt} = \frac{1}{m}\frac{dm}{dt} + \frac{1}{T}\frac{dT}{dt} \tag{10}$$

Thus, the rate of change of pressure w.r.t time in a control volume with variable volume is given by[1]

$$\frac{dP}{dt} = \frac{\gamma R}{V}(\dot{m}_{in}T_{in} - \dot{m}_{out}T_{out}) - \frac{\gamma P}{V}\frac{dV}{dt} \tag{11}$$

the rate of change of temperature w.r.t. time is given by[1]

$$\frac{dT}{dt} = \frac{RT^2}{VP}\left(\left(\gamma\frac{T_{in}}{T} - 1\right)\dot{m}_{in} - (\gamma - 1)\dot{m}_{out}\right) - \frac{(\gamma - 1)T}{V}\frac{dV}{dt} \tag{12}$$

where $V = V + Ax$ and $\frac{dV}{dt} = A\dot{x}$ (13)

When the volume of control volume decreases i.e. work is done on the control volume, the negative sign on the second term on the R.H.S. of equation (11) and (12) becomes positive. The mass flow rate into the control volume is given by

$$\dot{m}_{in} = C_d A_{in} P_{in}\sqrt{\frac{2\gamma}{(\gamma - 1)RT_{in}}}\,N \tag{14}$$

When the pressure in the control volume is above the critical pressure

$$N = \sqrt{\left(\left(\frac{P}{P_{in}}\right)^{\frac{2}{\gamma}} - \left(\frac{P}{P_{in}}\right)^{\frac{(\gamma+1)}{\gamma}}\right)} \tag{15}$$

When the pressure in the control volume is less than the critical pressure

$$N = \sqrt{\left(\left(\frac{2}{(\gamma + 1)}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{\gamma - 1}{2}\right)\right)} \tag{16}$$

The movement of the main and pilot poppets is found by applying the Newton's second law neglecting the friction forces. Forces in the opening direction of the poppet are considered positive. The motion of the main poppet is described in the equation below

$$M_1\ddot{x}_1 = P_2(Ab_1 - As_1) + P_3As_1 - P_4Ab_1 - FS_1 - FB_1 - K_1x_1 - B_1x_1 \tag{17}$$

The motion of the pilot poppet is described by

$$M_2\ddot{x}_2 = P_2(Ab_2 - Ast) + P_6As_2 - P_7Ab_2 - P_5(As_2 - Ast) - FS_2 - FB_2 - K_2x_2 - B_2x_2 \tag{18}$$

5. Modeling

The mathematical model of the valve and the related equations are derived by applying the governing equations to the valve block diagram shown in fig.3. This is generated using the orifice in series concept [6]. The equations for the tank and different chambers in the valve are given below.

Equations for Gas Tank

$$\frac{dP_1}{dt} = \frac{\gamma R}{V_1}(\dot{m}_c T_c - \dot{m}_{12}T_1) \tag{19}$$

$$\frac{dT_1}{dt} = \frac{RT_1^{\,2}}{V_1P_1}\left(\left(\gamma\frac{T_c}{T_1} - 1\right)\dot{m}_c - (\gamma - 1)\dot{m}_{12}\right) \tag{20}$$

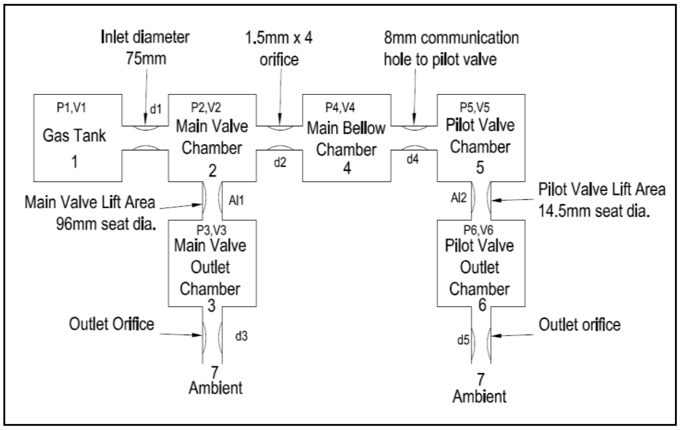


Fig. 3. Block Diagram of the Vent and Safety Valve

Equations for Main Valve Chamber

$$\frac{dP_2}{dt} = \frac{\gamma R}{V_2}(\dot{m}_{12}T_1 - (\dot{m}_{24}T_2 + \dot{m}_{23}T_2) \tag{21}$$

$$\frac{dT_2}{dt} = \frac{RT_2{}^2}{V_2P_2}\left(\left(\gamma\frac{T_1}{T_2} - 1\right)\dot{m}_{12} - (\gamma - 1)(\dot{m}_{24} + \dot{m}_{23})\right) \tag{22}$$

Equations for Outlet Chamber

$$\frac{dP_3}{dt} = \frac{\gamma R}{V_3}(\dot{m}_{23}T_2 - \dot{m}_{37}T_3) - \frac{\gamma P_3}{V_3}As_1\dot{x}_1 \tag{23}$$

$$\frac{dT_3}{dt} = \frac{RT_3{}^2}{V_3P_3}\left(\left(\gamma\frac{T_2}{T_3} - 1\right)\dot{m}_{23} - (\gamma - 1)\dot{m}_{37}\right) - \frac{(\gamma - 1)T_3As_1\dot{x}_1}{V_3} \tag{24}$$

Equations for Main Bellow

$$\frac{dP_4}{dt} = \frac{\gamma R}{V_4}(\dot{m}_{24}T_2 - \dot{m}_{45}T_4) + \frac{\gamma P_4}{V_4}Ab_1\dot{x}_1 \tag{25}$$

$$\frac{dT_4}{dt} = \frac{RT_4{}^2}{V_4P_4}\left(\left(\gamma\frac{T_2}{T_4} - 1\right)\dot{m}_{24} - (\gamma - 1)\dot{m}_{45}\right) + \frac{(\gamma - 1)T_4Ab_1\dot{x}_1}{V_4} \tag{26}$$

Equations for Pilot Valve Chamber

$$\frac{dP_5}{dt} = \frac{\gamma R}{V_5}(\dot{m}_{45}T_4 - \dot{m}_{56}T_5) \tag{27}$$

$$\frac{dT_5}{dt} = \frac{RT_5{}^2}{V_5P_5}\left(\left(\gamma\frac{T_4}{T_5} - 1\right)\dot{m}_{45} - (\gamma - 1)\dot{m}_{56}\right) \tag{28}$$

Equations for Pilot Valve Outlet Chamber

$$\frac{dP_6}{dt} = \frac{\gamma R}{V_6}(\dot{m}_{56}T_5 - \dot{m}_{67}T_6) - \frac{\gamma P_6}{V_6}As_2\dot{x}_2 \tag{29}$$

$$\frac{dT_6}{dt} = \frac{RT_6{}^2}{V_6P_6}\left(\left(\gamma\frac{T_5}{T_6} - 1\right)\dot{m}_{56} - (\gamma - 1)\dot{m}_{67}\right) - \frac{(\gamma - 1)T_6As_2\dot{x}_2}{V_6} \tag{30}$$

The area of flow due to lift of poppets is given by
For main poppet

$$Al_1 = \pi ds_1 x_1 \tag{31}$$

For pilot poppet

$$Al_2 = \pi ds_2 x_2 \tag{32}$$

6. Simulation

The above non-linear, coupled, first order, ordinary differential equations are solved for a given set of initial conditions and a forcing function (mass flow into the tank) using fourth order Runge-Kutta method [5]. The equation of motion is solved using Euler's method [5]. Additional constraints are introduced to obtain a physically feasible solution. The constraints are given below.

- The lift of the poppets cannot be negative since they cannot move below the reference which is the seating area. Hence any negative lift is assigned as 0.
- The corresponding velocity is also assigned as 0.This indicates that the poppet comes to a complete halt i.e. a plastic collision [1].
- The calculated lift of the poppet cannot be more than the maximum lift in the valve. Hence when the lift exceeds its maximum value, it is assigned its maximum value. The corresponding velocity is again assigned as 0.

Table 1. Nominal geometrical parameters of the valve.

Parameter	Symbol	Value	Unit
Main Valve inlet diameter	d1	75	mm
Communication Orifice	d2	1.5(4no.)	mm
Outlet Orifice	d3	25	mm
Pilot Valve inlet diameter	d4	8	mm
Pilot Valve outlet diameter	d5	8	mm
Main Valve seat diameter	ds1	96	mm
Pilot Valve seat diameter	ds2	14.5	mm
Tank Volume	V1	300	l
Main Valve Chamber Volume	V2	1.5	l
Outlet Volume	V3	0.5	l
Main Bellow Volume	V4	2.4	l
Pilot Valve Chamber Volume	V5	0.015	l
Pilot Valve Outlet Volume	V6	0.015	l
Maximum lift of main poppet	Lm1	14	mm
Maximum lift of pilot poppet	Lm2	1.7	mm
Main Valve spring stiffness	K1	5.95	N/mm
Pilot Valve spring stiffness	K2	9.7	N/mm

The simulation is carried out for a valve with geometrical parameters as given in table 1. The valve is simulated for ground conditions with the ambient as 1bar and 300K.

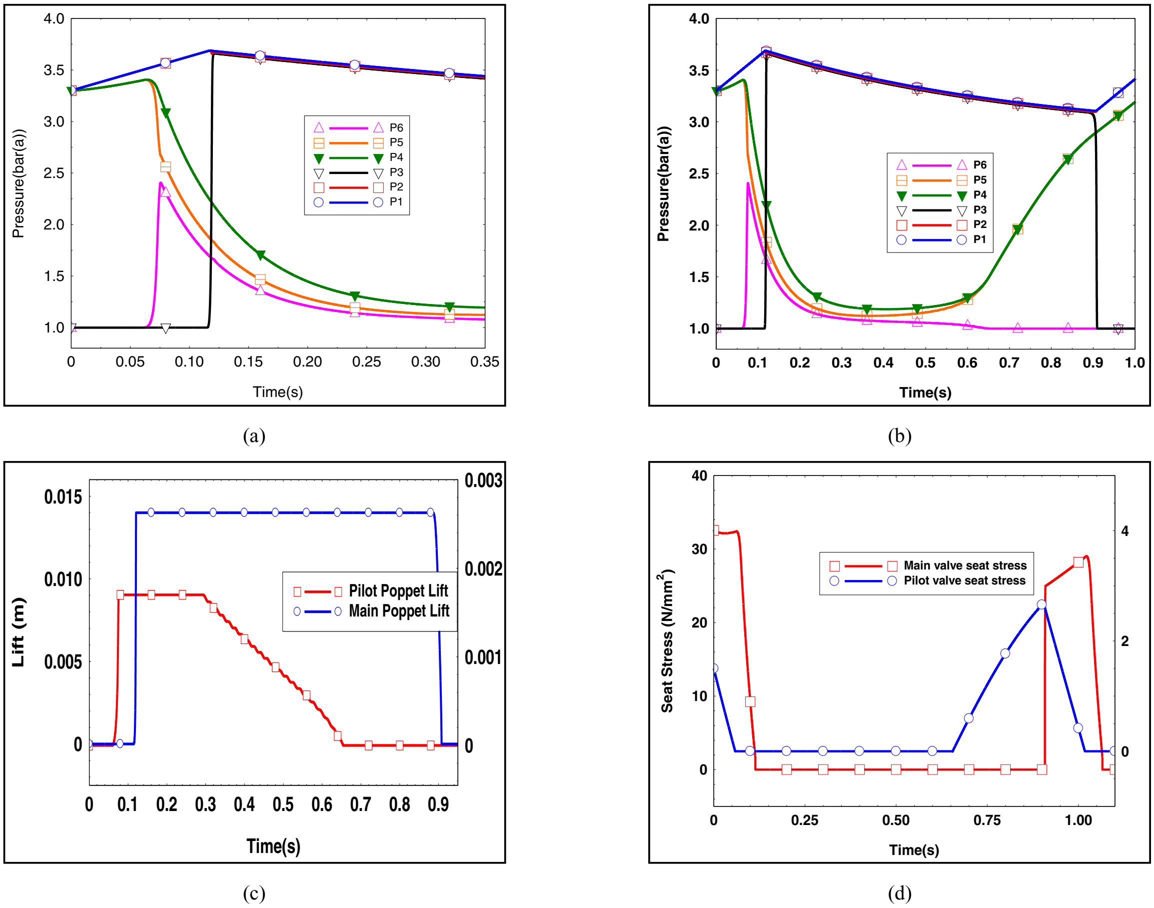


Fig. 4. Performance graphs of the nominal configuration; (a) start transient (b) closing characteristics (c) lift of pilot poppet and main poppet (d) seat stress in the valve

7. Results and Discussion

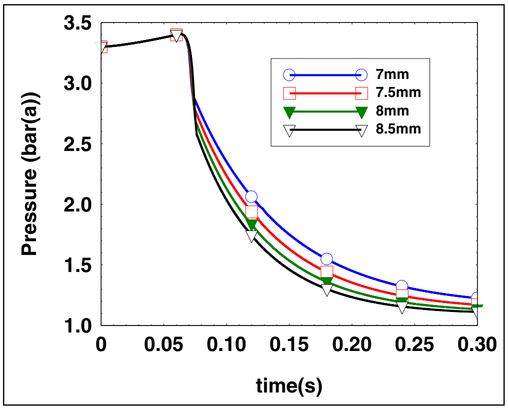
The results of simulation of the valve with the geometrical parameters mentioned in table 1, the forcing function as a constant input of 0.1kg/s of GHe at 300K for 3sec and initial tank pressure of 3.3bar are shown in the figures 4a, 4b, 4c, and 4d. Initially, the tank, volumes V2, V4 and V5 are at the same pressure of 3.3bar. As the flow inside the tank starts, the pressure inside the tank increases which is communicated to V2, V4 and V5.The inlet port d1 of the main valve is large (75mm) compared to d2 which results in P2 following P1 with a small drop of 0.01bar.The flow also takes place through d2 into V4 where a higher drop (0.11bar) takes place. This flow rate is lower due to which P4 rises at a rate lower than P2. Volume V4 is connected to V5, the pilot valve chamber, with an orifice of 8mm which is higher than d2 causing pressure P5 to follow P4. As both the pilot valve and main valve are closed, P6 and P3 are at ambient conditions of 1bar. As soon as P2 reaches 3.5bar, the cracking pressure of the pilot valve, the pilot poppet starts lifting. With increasing lift, P5 and P4 plummet as inflow (flow through d2) is not sufficient to revive P4 and P5 which drop due to outflow. The pilot poppet opens to its full lift within 15ms due to decreasing closing force (for which P5 is responsible) and increasing opening force (for which P2 and P6 is responsible). When the pressure inside the bellow reaches 2.3bar and P2 reaches 3.68bar, the differential force equals the spring and bellow initial load and the main poppet starts lifting. Due to faster drop of P4 from 2.3bar to 2.23bar in 4ms, higher bellow effective area and low stiffness spring, the main poppet goes to its full open position in only 5ms. The full flow pressure is 3.68bar which is same as the cracking pressure due to the sudden opening. The delay between the opening of main valve and pilot valve depends on the rate of decay of P4 which depends on d2 and d5. This delay which is 53ms for the given geometrical parameters in turn controls the cracking pressure of the valve. As soon as the main poppet lifts, flow takes place from the tank to the ambient through the outlet orifice. The valve lift area available is equivalent to a 74mm orifice which is higher than the outlet orifice of 25mm resulting in a back pressure of 3.66bar at the outlet volume. This back pressure aids opening and helps to keep the valve in open position. A full flow of 0.135kg/s of GHe is achieved which drops to 0.113kg/s before reseal. The tank pressure starts dropping whose decay is a function of tank volume, flow through the valve and inflow. With a decrease in the tank pressure, the opening force on the pilot poppet decreases. At a tank pressure of 3.48bar, the net force on pilot poppet becomes zero and the pilot poppet starts closing. The time taken by the pilot poppet from the start of closing to the full close position is 450ms which is much higher than its opening time. This is due to slower rate of decay of P2 than the rate of rise. At P2=3.21bar the pilot valve seals back. After this, the pressure P4 increases and the resulting closing force causes the main valve to seal back at P2=3.1bar. The time between pilot valve closing and main valve closing is 250ms which is a function of rate of rise of P4. The time for closing of main poppet is 20ms which is higher than its opening time due to the back pressure. The plot of seat stress is given in figure 4(d) which shows that as the tank pressure approaches its cracking value, the seat stress in pilot valve decreases but the seat stress in main valve increases reducing leakage.

8. Parametric Study

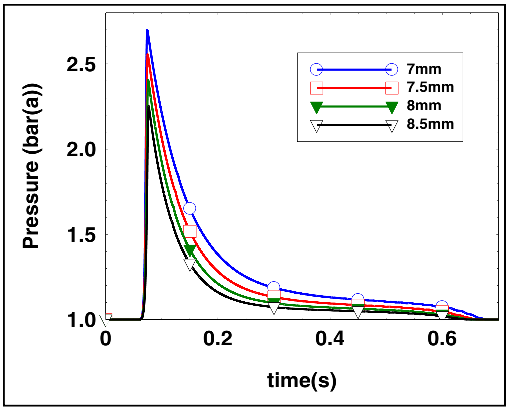
The valve has been studied with respect to the effect of geometrical parameters that control the performance of the valve. Four parameters viz. communication orifice, pilot valve outlet orifice, main valve outlet orifice and tank volume were varied and its effect was studied. During these simulations, all other parameters remain same as the nominal configuration.

8.1 Effect of pilot valve outlet orifice

The valve was simulated with d5=7mm to 8.5mm. With increasing d5, the area available for outflow of fluid from the main valve bellow chamber increases which helps the decay of P4 and hence the opening of the valve. With all other parameters constant, the cracking pressure of the main valve decreases by 0.03bar from d5=7mm to 8.5mm. The parameter d5does not have any effect on the reseal and closing characteristics of the main valve. The pilot valve closing is affected negligibly as the difference of pressures P5 and P6 for different d5 is minuscule. The simulation results are given in figure 5a and 5b.



(a)



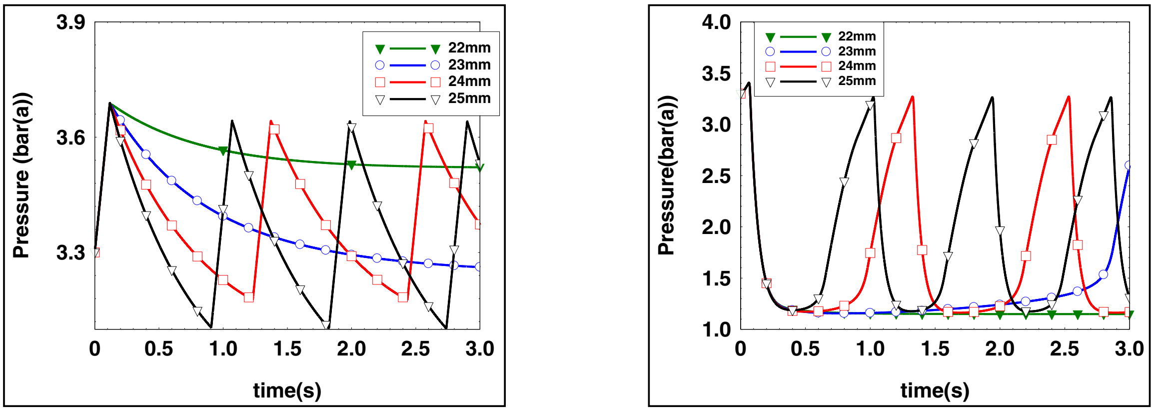
(b)

Fig. 5. Effect of pilot valve outlet orifice on; (a) pilot valve chamber pressure, P_5 (b) pilot valve outlet pressure, P_6

8.2 Effect of main valve outlet orifice

The outlet orifice d3 controls the flow through the valve and the back pressure buildup in the outlet chamber. It also controls the tank pressure decay. With decreasing d3, the flow rate decreases and hence the rate of pressure decay in the tank decreases. The value of d3 does not control the opening, initiation and completion of closing of the pilot poppet. Hence it does not have any effect on the opening of the main valve. For all d3, the pilot valve closes at the same pressure P2=3.21bar. This causes the bellow chamber pressure P4 to build up faster for lower d3 since a higher pressure P2 (due to lower rate of pressure decay) is available at the inlet of d2. Hence the main valve closes at a higher pressure P2 with decreasing d3 i.e. reseal pressure increases with decreasing d3 (3.1bar for d3=25mm, 3.17bar for d3=24mm, 3.27bar for d3=23mm). With a further decrease in d3 to 22mm, the valve reaches steady state condition where the flow through the valve equals 0.1kg/s of GHe which is the inflow into the tank. The P2 reaches a steady state value of 3.5bar. The pilot valve and the main valve remain in its full lift condition. The simulation results are given in figure 6a and 6b.

From the simulation, it can be concluded that the reseal pressure of the valve is sensitive to the rate of tank pressure decay which depends on the tank volume, outlet orifice and the forcing function.



(a) (b)

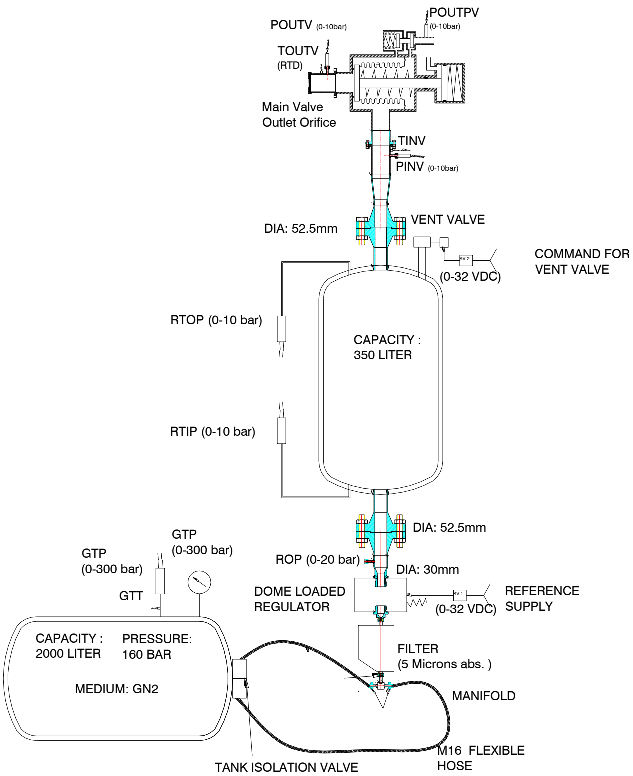
Fig. 6. Effect of main valve outlet orifice on; (a) cracking and reseal pressure (b) main bellow chamber pressure, P_4

9. Experimental Setup

The Vent and Safety Valve was assembled and tested at a high flow test facility located in LPSC, Trivandrum. The experimental setup is given in figure 7a and 7b. The Valve was mounted on a 350l Stainless Steel tank. The inlet of the tank was fed through a dome loaded pressure regulator (DLPR). High pressure nitrogen filled at 150bar in 2000l tank was the source of ambient gas to the tank. This gas was further regulated from a source pressure to a set tank pressure using the DLPR. The tank set pressure was varied by varying the dome pressure to the DLPR. Pressure transducers were mounted at the source cylinder, tank inlet, tank outlet, main valve inlet, main valve outlet and pilot valve outlet. Temperature sensors measured the temperature at the source cylinder and the main valve outlet locations.

10. Tests and Results

Initially the valve is in the closed position without any command. The cracking pressure of the pilot valve is set at 3.5bar. The high pressure at the source cylinder outlet is isolated from the downstream systems using a tank isolation valve. This valve is first opened to initiate the test sequence. The pressure is then communicated to the DLPR. The tank will not receive any gas until the dome of the DLPR is pressurised. This dome pressure, being supplied externally, controls the tank pressure. As soon as dome pressure is applied, the pressure in the tank rises. At a pressure of 3.46bar, the pilot valve opens and within 40ms the main valve pops open at 3.48bar. Using the temperature and pressure measurements upstream of main valve outlet orifice, the full flow rate, which starts at the same pressure as that of cracking, is 310g/s of GN2.



(a)

(b)

Fig. 7. Experimental Setup; (a) Test Schematic (b) Photograph of the test setup

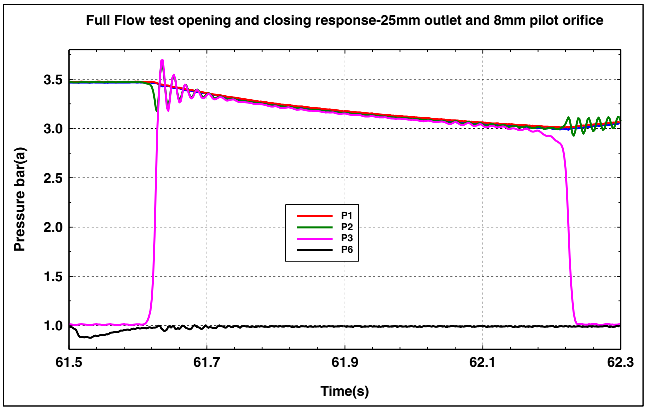


Fig. 8. Test Results with 25mm main valve outlet orifice and 8mm pilot valve outlet orifice

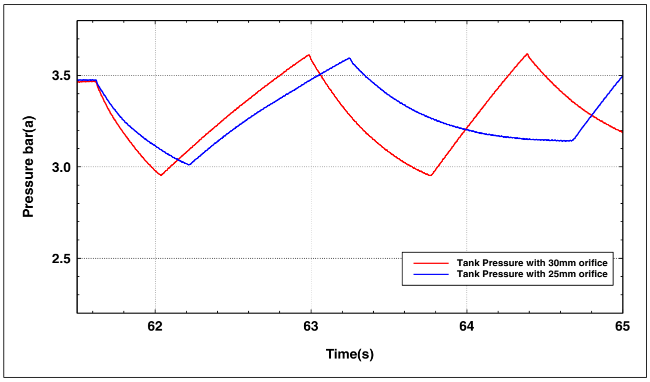


Fig. 9. Test Results; Variation in cracking pressure with main valve outlet orifice

11. Conclusions

A non-linear dynamic model for an inverted type pilot operated vent and safety valve has been generated and simulated for varying geometrical parameters to study its effect. The results of the simulation validate the analytical design and help in building a confidence that the valve will achieve its intended performance. Following conclusions can be drawn

- The simulation indicates that the main poppet will go to its full lift (pop open) as soon (5ms) as it opens which is why it is called as a “safety valve”. The pilot valve opens and goes to its full lift at its set pressure of 3.5bar at all conditions.
- The pilot valve outlet orifice causes the cracking pressure to increase with its decrease. It has no effect on the closing characteristics of the valve.
- The outlet orifice of the main valve controls the flow through the valve and consequently the rate of tank pressure decay. With change in outlet orifice, the cracking pressure of the valve remains same but the reseal pressure increases with decreasing orifice size. To get the reseal pressure within acceptable limits, a combination of communication orifice and outlet orifice needs to be selected which can be predicted with the model.

- The test results do not exactly replicate the simulation results quantitatively, but they definitely are similar qualitatively. Due to different interfaces and number of variables involved, the exact test setup was not modeled which is the cause of variations in the test results and the simulation results.

This model serves as a tool for arriving at the approximate geometric parameters required to obtain the desired performance before any tests.

References

[1] Nabi A., Wacholder E., Dayan J., “Dynamic Model for aDome-Loaded Pressure Regulator”, Journal of Dynamic Systems, Measurement, and Control, Transactions of the ASME, June 2000, Vol. 122, pp. 290-297.
[2] Dasgupta K., Karmakar R., “ Dynamic Analysis of a pilot operated pressure relief valve”, Simulation Modelling Practice and Theory, Elsevier,October 2002, Vol. 10, Issues 1–2, pp. 35–49
[3] Cengel Y.A., Boles M.A., “Thermodynamics : an Engineering approach ”, 5th Edition ,McGraw-Hill , New York
[4] Howell G.W., Weathers T.M., “Aerospace Fluid Component Designer’s Handbook”, February 1970, Vol.1, Rev.D
[5] Chapra S.C., Canale R.P., “Numerical Methods for Engineers”,4thEdition, Tata McGraw Hill
[6] Andersen B.W., “The Analysis and Design of Pneumatic Systems “, Wiley, 1967, New York.